

## Solar Irradiance

Irradiance is the power from a source of radiant energy that is incident on unit area of a surface located at some distance from the source. The Sun's total irradiance is  $1365 \pm 2 \text{ W m}^{-2}$ . This is the total radiant energy per unit time (i.e. power) at all wavelengths that the Earth receives on unit area of its surface from the entire solar disk when separated from the Sun by one astronomical unit ( $1 \text{ AU} = 1.49 \times 10^{13} \text{ cm}$ ).

Spectral irradiance is the power per unit area attributable to radiation within a specified wavelength interval. The Sun emits radiation that ranges in wavelength across the entire electromagnetic spectrum, from very short-wavelength x-rays, to ultraviolet (UV), visible, infrared (IR) and very long-wavelength radio waves. Figure 1 illustrates the dependence of solar spectral irradiance on wavelength, a dependence that covers more than six orders of magnitude and peaks in the visible spectrum.

Solar irradiance is not constant. Although the total irradiance has in the past been termed the solar 'constant', levels of total and spectral irradiance fluctuate continuously in concert with solar activity (see SOLAR ACTIVITY). During recent epochs of high solar activity, near maxima of the 11 year solar cycle (see SOLAR CYCLE), mean levels of total irradiance increased by about 0.1% ( $1.3 \text{ W m}^{-2}$ ) relative to solar cycle minima levels. Spectral irradiance also increases with solar activity, by different amounts depending on wavelength, as shown in figure 1 for a recent 11 year cycle. Small increases of less than a few tenths of a per cent occur at visible and near-infrared wavelengths, whereas radiation at the shortest x-ray and longest radio wavelengths can change by factors of two and more. Note that the actual radiant energy falling on the Earth varies by  $\pm 3\%$  annually because of regular changes in the distance of the Earth from the Sun. This wavelength-independent fluctuation is not intrinsically solar but, rather, a geometrical effect. Solar irradiance variability refers to changes arising in the Sun itself, specified at a fixed Sun–Earth distance of 1 AU.

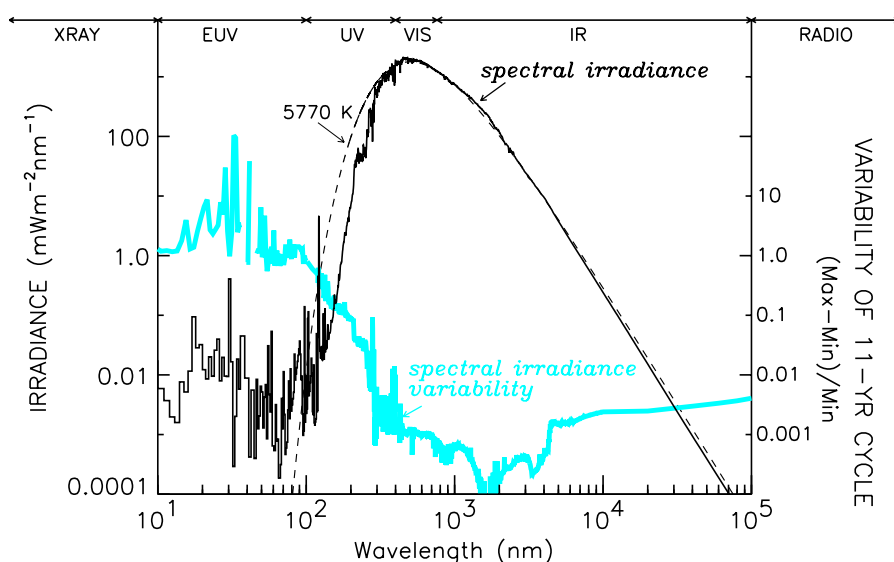
Acquiring reliable observations of solar irradiance has proven a challenging technological task. The longest continuous irradiance database—that of total (i.e. spectrally integrated) irradiance—has yet to cover two 11 year solar activity cycles. Since the late 1970s, more than five total irradiance instruments on various space platforms have utilized electrical substitution cavity pyrheliometers to achieve total irradiance measurements with uncertainties approaching  $\pm 0.2\%$  and long-term repeatabilities of the order of  $\pm 0.01\%$ . Spectral irradiance observations are less reliable and less frequent than are total irradiance observations. Even in the UV spectrum, where most spectral irradiance measurements have been made, uninterrupted monitoring has yet to be accomplished for a complete solar cycle. Using combinations of redundant gratings and filters (to achieve spectral dispersion), photoelectric detectors and on-board

calibration tracking, solar UV spectroradiometers that have operated continuously in space since late 1991 are at present achieving uncertainties in the range  $\pm 6\text{--}10\%$ , and long-term repeatabilities approaching  $\pm 1\%$ . Regular monitoring of the Sun's visible and infrared spectrum remains to be undertaken.

Close physical relationships between the Sun's radiative output and magnetic fields in the solar atmosphere (see SOLAR MAGNETIC FIELD) facilitate the primary mechanisms of solar irradiance variability. Magnetic fields, when present in the Sun's atmosphere, perturb its radiative processes by altering temperature and density (see, for example, SOLAR SPECTROSCOPY AND DIAGNOSTICS). Thus, magnetic active regions (see ACTIVE REGIONS) are sites of local enhancement or depletion of solar radiation. Particularly important for their effects on solar irradiance are dark sunspots—in which radiation is depleted (see SUNSPOTS)—and bright faculae—which are sources of enhanced radiation (see SOLAR PHOTOSPHERE). The variable occurrence and inhomogeneous distribution of both sunspots and faculae on the solar disk throughout the solar cycle produce net fluctuations in irradiance (i.e. the emission from all radiative sources integrated over the entire disk), with strong wavelength dependences. Particularly significant perturbations ( $>100\%$ ) occur in emissions at the shortest (x-ray) and longest (radio) wavelengths that are formed in the highest and hottest layers of the solar atmosphere.

Past and future solar irradiance variability potentially exceed the range detected by space-based solar irradiance observations. Compared with historical proxy records of solar activity, including sunspot and geomagnetic records, and cosmogenic archives in ice cores and tree rings, current solar monitoring has been accomplished during an epoch of overall high levels of solar activity and larger than average 11 year cycle amplitudes. Associations of modern magnetic sources with historical solar activity proxies suggest that total irradiance may have increased a few tenths of a per cent since an epoch of anomalously low solar activity during the seventeenth century. Called the Maunder minimum, this episode of solar quiescence appears to be but the most recent of similar episodes that have occurred semiregularly in the Sun's multicentennial past, and are expected in its future.

Solar irradiance is the primary energy source for the Earth. Thus it is a crucial geophysical quantity for modeling and understanding a myriad of terrestrial processes including global climate change and space weather (see SOLAR–TERRESTRIAL CONNECTION). Radiation at wavelengths longer than 300 nm penetrates though most of the Earth's atmosphere to within 15 km of the surface. This radiation comprises 99% of total irradiance and its fluctuations have long been speculated to alter surface temperatures and other climatological phenomena on decadal and centennial time scales, vying with greenhouse gases and sulphate aerosols in the industrial epoch. The Earth's atmosphere absorbs the remaining 1% of the Sun's irradiance, including the high-energy UV, extreme



**Figure 1.** The spectrum of the Sun's radiation incident on top of the Earth's atmosphere (thin dark curve), and of a blackbody at 5770 K (thin dashed curve). The Sun's total irradiance is the integral over all wavelengths of this spectral irradiance. The broad spectral bands identified along the top of this figure are designated the extreme ultraviolet (EUV), ultraviolet (UV), visible (VIS) and infrared (IR). The x-ray spectrum lies shortward of the EUV spectrum and at wavelengths longward of the IR is the microwave or radio portion of the solar spectrum. Also shown (thick gray curve) are estimates of the variations in solar spectral irradiance for a recent 11 year activity cycle. At wavelengths longer than 400 nm these estimates are speculative because very limited observational data exist.

ultraviolet (EUV) and x-rays. These radiations would have detrimental biological effects were they able to penetrate to the Earth's surface. Rather, short-wavelength solar radiation provides the primary energy input to the atmosphere, where it initiates and controls the ozone layer in the stratosphere and, at higher altitudes, the ionosphere and thermosphere. More variable by orders of magnitude than the total irradiance, solar ultraviolet emissions may impact global change indirectly through middle atmosphere coupling with the biosphere. Solar heating and ionization perturbations of the upper atmosphere by highly variable extreme ultraviolet radiation impact communications and satellite drag.

### Spectrum of the Sun's radiation

The spectrum of the Sun's radiation—its distribution of irradiance with wavelength, shown in figure 1—is a combination of continuum, emission and absorption features. Solar continuum radiation has a smoothly varying spectral shape similar to that of a black body near 5770 K (also shown in figure 1), which is the approximate temperature of the Sun's visible surface. The Sun's surface is defined as the layer of its atmosphere from which radiation at 500 nm (near peak irradiance levels of the blackbody spectrum) emerges with unit optical depth. Most (>99%) of the Sun's irradiance—that at wavelengths from 160 nm to 5  $\mu\text{m}$ —also emerges from the vicinity of the solar surface, in a layer of the Sun's atmosphere a few hundred kilometers thick called the photosphere.

Numerous emission and absorption lines are superimposed on the dominant solar continuum. Gases in the

Sun's atmosphere cause these spectral features by either absorbing the underlying continuum radiation (producing, for example, Fraunhofer lines) or by augmenting the continuum radiation with local emission processes. Least absorption by the solar atmosphere of the underlying photospheric continuum emission occurs in the vicinity of 1.6  $\mu\text{m}$  (1600 nm). This radiation thus emerges from the deepest observable layers of the Sun and is the least variable region of the solar spectrum (see figure 1).

Many species in the solar atmosphere, for example Al, Mg, Ca, O, Fe, He and H, absorb radiation at UV, visible and IR wavelengths. In the visible and infrared spectrum their absorption lines are superimposed on the dominant 5770 K blackbody continuum. In the UV spectrum, however, this line absorption is so strong that it depletes significantly the underlying continuum radiation. At about 500 km above the Sun's visible surface the solar atmosphere temperature has a minimum value of 4500 K that delineates the upper boundary of the solar photosphere from the overlying chromosphere and corona. The solar spectra near 160 nm and from 75  $\mu\text{m}$  to 300  $\mu\text{m}$  originate near this temperature minimum region.

Radiation at wavelengths increasing shortward of 160 nm and longward of 300  $\mu\text{m}$  emerges from increasingly higher, and generally hotter, layers of the solar atmosphere. In the solar chromosphere and corona temperatures in the range of  $10^4$  to  $10^6$  K produce excited and ionized states of atoms. Emission processes of these species emit radiation with characteristic spectral signatures whose strengths depend on the local temperature and composition of the solar atmosphere. Of

these features, the emission by Hydrogen I produces the strongest line, at 121.57 nm, clearly evident in figure 1. Although the net irradiance of line emission at EUV and x-ray wavelengths is many orders of magnitude less than the visible continuum irradiance, it nevertheless exceeds by orders of magnitude the blackbody radiation in this short-wavelength spectral regime.

### Observations of total irradiance

Attaining reliable observations of the Sun's total irradiance—the energy radiated at all wavelengths—has been a goal for more than a century, motivated by the need to specify fluctuations in the radiative energy input to the Earth. On the basis of observations made with ground-based instrumentation from 1874 to 1976, the total irradiance of the Sun was considered to be invariant with time, and hence designated the solar 'constant'. But the measurements lacked the accuracy and repeatability to establish either the correct absolute value of the irradiance, or its variability, to better than about half a per cent.

During the past two decades, solar radiometers flown on orbiting spacecraft (to eliminate interference by the Earth's atmosphere) have detected real total irradiance variability at levels of tenths of a per cent. These observations have achieved uncertainties in absolute calibration of  $\pm 0.2\%$  and long-term repeatabilities better than 0.01% by utilizing the technique of electrical substitution radiometry, combined with detailed characterization and monitoring of in-flight sensitivity changes in the radiometers. A cavity in the instrument collects solar photons independently of their wavelength. The inside surface of the cavity is blackened and shaped so that every absorbed photon contributes thermal energy when a shutter permits solar radiation to reach the cavity. With the shutter closed, electrical power substitutes for the radiant power to maintain the cavity at a constant temperature. Knowing the aperture of the cavity then provides a direct measure of the incident total irradiance in absolute units of power per unit area ( $\text{W m}^{-2}$ ), at the known distance of the cavity from the Sun.

The five or more radiometric instruments that have observed the Sun's total irradiance at various times during the past two decades have each realized a slightly different absolute scale, uncertainty and long-term stability. The various instruments have different cavity, baffle and aperture geometries, thermal losses, drift compensations and electronic readouts, and have flown on space platforms with different thermal stabilization and pointing capabilities. Figure 2 shows a composite record of daily mean total irradiance obtained from the cross-calibration of overlapping datasets to adjust for scale differences, taking into account drifts in the sensitivities of the individual radiometers during different phases of their missions. Whereas the time series in figure 2 presents the most probable observational record of the Sun's total irradiance, individual radiometric data at times deviate notably from this composite record, and from each other, because of instrumental sensitivity drifts. A

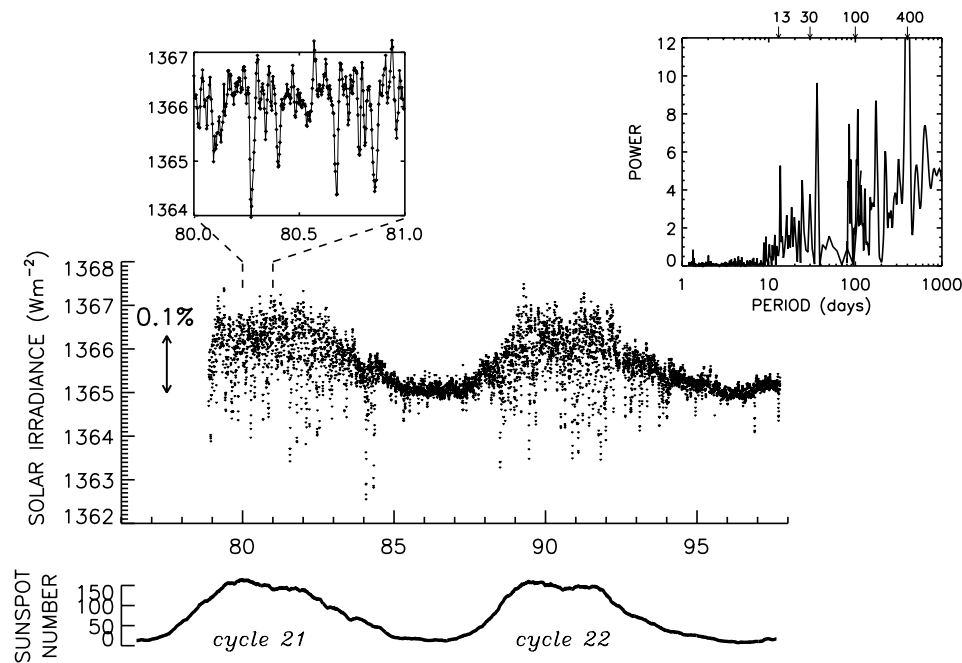
primary cause of these drifts is solar exposure itself, which alters the blackness of the cavity surface and affects the thermal energy conversion. Drifts in temperature-sensitive electrical components and in the orientation of the cavity to the Sun also contribute. The most successful observations of total irradiance are achieved from instruments that utilize a number of redundant cavities with widely different duty cycles to effect in-flight calibration tracking, and that are mounted on thermal- and view-stabilized platforms.

Time scales of variability present in the observational record of total irradiance range from decades to minutes. Prominent in the composite record in figure 2 is an 11 year cycle that tracks closely the solar activity cycle, represented in this figure by the smoothed sunspot number. Monthly to yearly irradiance changes reflect the impact of the evolution of magnetic complexes that comprise sunspots and faculae. Significant irradiance dips of a few tenths of a per cent on a monthly and semimonthly cadence are associated with the impact on solar irradiance of the Sun's rotation on its axis. This rotation modulates irradiance by presenting different populations of magnetic active regions to the Earth's view. Peaks in the power spectrum shown in figure 2 identify these effects near 13 and 30 days and in additional longer period peaks. Total irradiance responds as well to the 5 min pressure mode oscillation of the solar interior (see *HELIOSEISMOLOGY: THEORY, HELIOSEISMIC OBSERVATIONS*), and possibly to the hourly time scales of gravity modes as well, but these fluctuations are not resolved in the daily mean data in figure 2.

At present two instruments are monitoring the Sun's total irradiance from space: the Active Cavity Radiometer Irradiance Monitor (ACRIM II) on the Upper Atmosphere Research Satellite (UARS, launched in 1991) and the Variability of Irradiance and Gravity Oscillations (VIRGO) instrument on the Solar Heliospheric Observatory (SOHO, launched in 1995). NASA's Earth Observing System (EOS), the European Space Agency (ESA) attached pallet to the International Space Station (ISS), France's CNES and the US National Polar-orbiting Operational Environmental Satellite System (NPOESS) each have programs for subsequent measurements. Acquiring reliable knowledge of the Sun's total irradiance variability on decadal time scales, independent of instrumental drifts, will require the indefinite continuation of solar irradiance monitoring using radiometers with greater stability than those that have flown in the past two decades, mounted on space platforms with highly stabilized thermal and pointing environments.

### Observations of spectral irradiance

Reliable observations of the Sun's spectral irradiance must, like those of total irradiance, be made from space to avoid contamination by the Earth's overlying atmosphere. In particular, the solar spectrum at wavelengths shorter than 310 nm can only be observed from space as the Earth's atmosphere absorbs this radiation entirely. Because of their importance for understanding processes



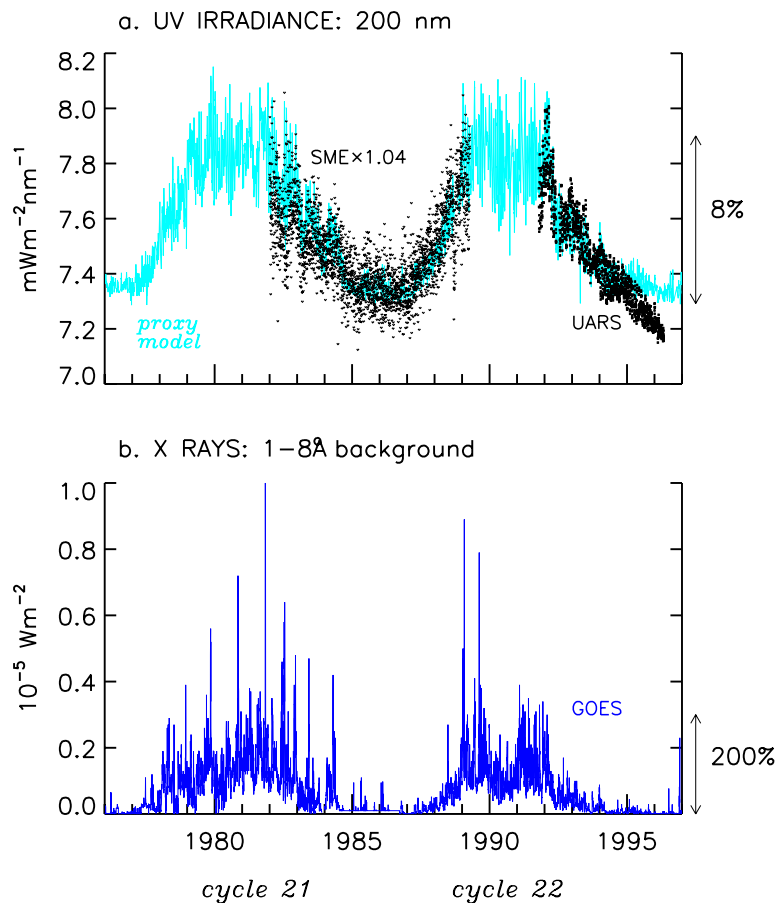
**Figure 2.** Daily mean values of the Sun's total irradiance are shown from 1979 to 1997. This composite irradiance record was constructed from observations made by four different solar radiometers at various times throughout the epoch. Evident is a pronounced 11 year cycle with an approximate peak-to-peak magnitude of 0.1%, on which are superimposed larger weekly to monthly fluctuations of a few tenths of a per cent. The 11 year total irradiance cycle tracks the general level of solar activity, indicated by the sunspot numbers in the lowest plot. The subset of data shown in the upper left hand plot provides details of rotational modulation, and the power spectrum in the upper right hand plot summarizes various apparent cycles in the composite total irradiance record.

in the Earth's atmosphere, the UV, EUV and x-ray regions of the solar spectrum have been monitored far more frequently than has any other part of the solar spectrum. But even these shorter-wavelength measurements have, over the past two decades, been made only intermittently. Except for two narrow x-ray bands, which Geostationary Operational Environmental Satellites (GOES) have monitored operationally since the 1970s, continuous reliable time series of solar spectral irradiance have not been procured for even one 11 year solar cycle. Figure 3 provides a sample of UV spectral irradiance monitoring—that made of the upper photospheric emission at 200 nm by instruments on the UARS and Solar Mesosphere Explorer—and of the coronal soft x-ray 0.1–0.8 nm fluxes.

Solar spectral irradiance instruments typically operate only over a limited wavelength range. They achieve wavelength discrimination by employing optical elements, usually gratings or spectral band filters, to disperse or select specified bands of the solar spectrum. Since narrow wavelength bands comprise significantly less solar power than the  $1365 \text{ W m}^{-2}$  total irradiance, spectral irradiance instruments utilize detectors, typically photomultipliers or diodes, which have sensitivities higher by many orders of magnitude than that of an electrical substitution cavity. These detectors amplify the small signal incident on them from the dispersing element when it is

positioned at a known wavelength setting. Unlike total irradiance radiometers, spectral irradiance instruments are not electrically self-calibrating. Rather, pre-flight laboratory calibrations and characterizations establish the absolute irradiance scale at each wavelength by using standard irradiance sources and detectors. For all but the most recent UV spectral irradiance measurements, whose uncertainties approach  $\pm 6\%$ , pre-flight calibrations of instruments typically achieve uncertainties in the range  $\pm 10\text{--}50\%$ . On-orbit sensitivity degradation can introduce additional large uncertainties to long-term monitoring of spectral irradiance variability. Only the most recent UV spectral irradiance instruments, those flying on the UARS, have the capability for on-orbit calibration tracking of these changes, and achieve long-term repeatabilities approaching  $\pm 1\%$  at some UV wavelengths.

Significant instrumental uncertainties are present in the historical database of solar spectral irradiance observations, arising from different realizations of absolute spectral irradiance scales combined with in-flight sensitivity drifts of the instruments. Exposure to solar radiation degrades the reflectivities and transmittances of optical elements in solar spectroradiometers; slippage in grating drive mechanisms contributes uncertainties in the wavelength of the radiation. At most wavelengths in the solar spectrum, the uncertainties in the historical irradiance database are comparable to, or exceed, the



**Figure 3.** Variations occur in the Sun's radiation at wavelengths throughout the spectrum, and are shown in (a) the UV 200 nm irradiance measured by instruments on the SME and UARS spacecraft and (b) the GOES 1–8 Å background flux measured by a series of operational spacecraft. These spectral irradiance variations occur in concert with solar activity, whose long-term changes produced the variable sunspot record in figure 2. An empirical solar variability model that utilizes a facular proxy to estimate the 200 nm irradiance is also shown (gray line) for comparison with the SME and UARS 200 nm irradiance observations, which do not overlap in time and which cannot therefore be cross-calibrated to remove instrumental calibration scale differences.

amplitude of the solar cycle variability itself. In the visible and infrared solar spectrum, monitored by only a very few filter radiometers, instrument sensitivity changes in the range 5–50% far exceed the real solar variations which are thought to be in the range of a few tenths of a per cent; reliable observational determination of solar visible and infrared spectrum variability has thus far not been achieved. Knowledge of the irradiance and variability of even the strongest line in the entire solar spectrum—the emission of hydrogen Lyman  $\alpha$  (121.6 nm)—remains uncertain by 30% to 50%, as does that of most EUV emission lines. Only in the spectral region from 250 to 120 nm have instrument sensitivity drifts been tracked with a repeatability of a few per cent, sufficient to estimate solar cycle changes of order of 3–30%, but these data exist thus far for less than one 11 year cycle.

In spite of their limitations, the available spectral irradiance measurements have established beyond doubt that the solar spectrum varies in concert with solar activity

over multiple time scales. As shown in figure 1 for a typical 11 year activity cycle, the amplitude of the variability is strongly wavelength dependent. Spectrum variability occurs on time scales shorter than the solar cycle because active region evolution, solar rotation and interior oscillation also modulate spectral irradiance, in different degrees depending on the source of the irradiance within the solar atmosphere. In general, the emissions formed in higher, hotter solar atmospheric layers vary the most. Coronal x-rays are seen in figure 3(b) to vary by two orders of magnitude; these emissions are highly sensitive to magnetic activity, especially eruptive instabilities that produce flares, but they are insensitive to interior oscillations. EUV radiation from the solar chromosphere and transition region can vary by factors of two or more and UV radiation by a few to 50%; the 200 nm fluxes shown in figure 3(a) decreased by 8% from the maximum to minimum of the most recent 11 year cycle. Radiation formed in the vicinity of the Sun's surface is the

least variable with solar cycle amplitudes of no more than a few tenths of a per cent. This radiation is insensitive to flares and sensitive to interior oscillations, which are detectable in irradiance time series made with sufficiently high time resolution.

At present, two instruments also on board the UARS are measuring solar spectral irradiance at wavelengths from 120 to 420 nm in 1 nm bands. These are the Solar Stellar Irradiance Comparison Experiment (SOLSTICE) and the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM). GOES spacecraft continue operational solar x-ray monitoring, augmented since mid 1991 by soft x-ray observations made using an imaging (rather than full disk flux) instrument on board the Yohkoh spacecraft. Apart from VIRGO's filter radiometers on SOHO, which cover three selected near-UV, visible and IR narrow (5 nm) bands, the solar visible and IR spectrum is not monitored at present. Future programs include observations of the total and spectral irradiances by EOS, ESA and NPOESS, and of the EUV spectral irradiance by the Thermosphere Ionosphere Mesosphere Energetics and Dynamics spacecraft. Apart from NPOESS, these programs are of insufficient duration to determine long-term spectral irradiance trends, but they will advance significantly knowledge of shorter-term spectral irradiance variability.

### Mechanisms of present irradiance variability

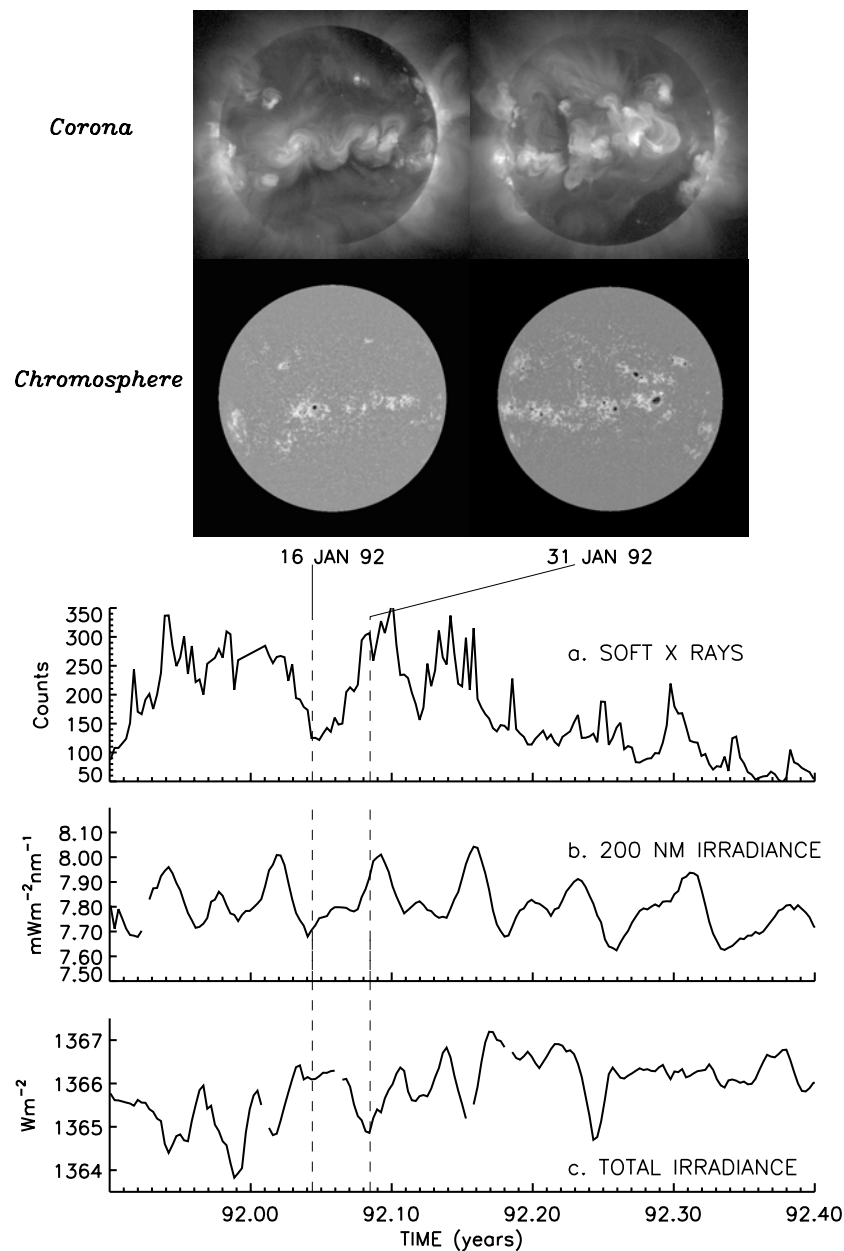
Mechanisms of solar irradiance variability arise from the fundamental connections between radiation and magnetism in the Sun's atmosphere. The prominent 11 year cycles in the total and spectral irradiance in figures 2 and 3 are simply global manifestations of these connections. So too are irradiance fluctuations that track multimonthly evolution of active regions, the 27-day rotation of the Sun on its axis, and a range of shorter time scale variability related to meso- and super granulation (see SOLAR PHOTOSPHERE: MESOGRANULATION; SUPERGRANULATION). In each case, the eruption, rearrangement and disappearance of magnetic fields in the solar atmosphere modify the Sun's radiative output. Magnetic fields perpetrate distinctive features in different solar atmosphere regimes, as displayed in the images in figure 4. These features, which include dark sunspots and bright faculae, affect solar irradiance at different wavelengths in different ways. Thus, the three time series in figure 4, of total, UV and x-ray irradiances emitted from respectively the photosphere, upper photosphere and corona, exhibit markedly distinct temporal variability even though solar magnetism is ultimately their common origin.

In the photosphere near the Sun's surface, from whence emerges near-UV, visible and IR radiation, sunspots are the pre-eminent signature of solar magnetism. Formed by compact clumps of magnetic fields, sunspots are darker and cooler than the surrounding photosphere because the magnetic fields inhibit the upward

flow of energy from the Sun's convection zone to its visible surface. Less compact aggregates of magnetic field lines also abound in the photosphere. Being only slightly brighter than the surrounding photosphere, and much less compact than sunspots, these features, the faculae, are barely detectable in images of the solar disk recorded with visible continuum radiation, except near the limb. However, because of their greater dispersion over the entire solar surface they are equally important in modifying the net radiative output of the Sun (see FACULAE, SOLAR PHOTOSPHERIC MAGNETIC FLUX TUBES).

Hundreds of kilometers above the Sun's surface the primary evidence of magnetic fields are bright, rather than dark, activity features. In the largest of these regions, called plage, magnetic fields clump together to form complexes of activity that extend over much more of the solar disk than do the compact sunspots. Bright emission is also present in a network that covers most of the solar surface, and in a range of interspersed magnetic features that have smaller spatial scales than active regions. Plage and network are evident as regions of enhanced emission in the image of the Sun's chromosphere in figure 4 made in the core of the Ca K Fraunhofer line. These bright magnetic features are the chromospheric counterparts of photospheric faculae, and are sources of significantly enhanced UV and EUV emission from the upper photosphere, chromosphere and transition region. Thus the fluctuations in solar UV and EUV spectral irradiance track closely the evolution of bright faculae, with little discernible sunspot influence. Higher still, in the Sun's corona, magnetic fields form bright loops and extended magnetic complexes that obliterate distinct connections to sunspots, plage and network below. As seen in the Yohkoh soft x-ray images in figure 4, coronal magnetic structures at times extend over much of the solar disk; they emit prodigious levels of x-ray, EUV and radio flux and control irradiance variability at these wavelengths.

Specific knowledge of the areas and brightnesses of the various magnetic features present in different solar atmospheric regimes permits the empirical modelling of solar irradiance variability for comparison with directly observed irradiance data at different wavelengths. Ground based, visible light solar images record areas and locations of sunspots that are used to calculate sunspot darkening contributions. Other spectroheliograms, such as the Ca K images in figure 4, record the locations and areas of enhanced emission in plage, faculae and the surrounding bright network. Solar variability models that combine, in different amounts, global parametrizations of these two components can explain much of the observed irradiance variability from the photosphere and chromosphere. A model with significant contributions from both sunspot darkening and facular brightening accounts for almost 90% of the variance in the daily mean total irradiance data over nearly two decades, shown in figure 2. In comparison, the model estimates shown in figure 3(a), used to cross-calibrate two on-overlapping



**Figure 4.** Solar activity and solar rotation alter the distribution of magnetic features in the solar atmosphere, viewed from Earth, as shown in two types of solar images made in 1992 near maximum levels of solar activity. These changes generate irradiance variability. Soft x-ray (upper) images measured by the Yohkoh spacecraft display the changing occurrence of global-scale magnetic features in the corona. Ca II K (lower) images measured at the Big Bear Solar Observatory show related but less extended magnetic features present in the chromosphere on the same days. Soft x-rays fluxes measured by Yohkoh (a), the UV 200 nm irradiance measured by UARS (b) and total irradiance (c) measured by ACRIM on UARS track the changing distributions of active regions projected toward Earth during solar rotation and over the solar cycle.

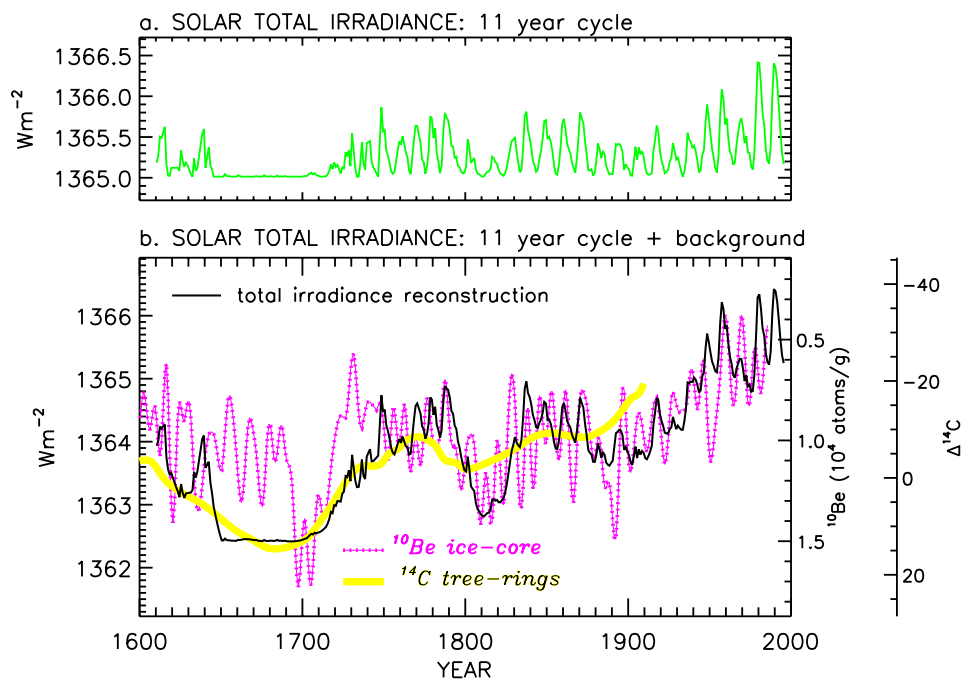
datasets of UV 200 nm irradiance, utilizes the facular component alone.

### Irradiance variability on historical time scales

How might solar irradiance have varied in the past, and what are the prospects for future variability? Astrophysics

and geophysics both motivate the need for this understanding. Examining long-term variability of other stars like the Sun can provide clues about broader aspects of stellar evolution (see SOLAR-STELLAR CONNECTION); and long-term solar variability has implications for terrestrial climate and global change on centennial time scales and





**Figure 5.** Reconstructions of the Sun's total irradiance, assuming in (a) an 11 year cycle alone and in (b) the 11 year activity cycle and a longer-term component based on the average amplitude of each sunspot cycle. This latter irradiance reconstruction (dark solid curve) is compared with  $^{10}Be$  (small squares) and  $^{14}C$  (thick gray curve) cosmogenic isotope records.

longer, thereby aiding in the specification of natural climate variability for comparison with anthropogenic influences (see SOLAR–TERRESTRIAL CONNECTION: LONG-TERM AND SHORT-TERM CLIMATE VARIABILITY).

A variety of solar, geomagnetic and geological records contain information about long-term solar activity fluctuations and the irradiance changes that presumably accompanied these fluctuations. Images of the Sun that depict sunspots have been made from ground based observatories since the seventeenth century, including during the Maunder minimum when for many years sunspots occurred only very infrequently. Conceptually, the sunspot record indicates that solar activity increased from anomalously low levels during the Maunder minimum to the present epoch of frequent sunspot occurrence with numbers as high as any witnessed during the past 400 years. Furthermore, indices of geomagnetic activity recorded at the Earth during the past 150 years indicate an overall upward activity trend concurrent with increasing solar cycle amplitudes. Geological records of  $^{14}C$  and  $^{10}Be$  cosmogenic isotopes in, respectively, tree rings and ice cores confirm that overall levels of solar activity have increased during the past three centuries. The isotope levels reflect variations in the terrestrial flux of galactic cosmic rays that arise from solar activity modulation of the magnetic coupling of the Sun and the Earth. Consistent with the evidence from sunspots, geomagnetic data and cosmogenic isotopes, the Sun's present activity is in the high range of levels seen in a collection of solar-like stars.

Two decades of space-based solar irradiance monitoring has thus been conducted during an era of overall high solar activity compared with levels during the past few centuries. This suggests the plausibility of solar irradiance levels lower than any yet observed in recent solar cycle minima, for example during the Maunder minimum. Speculated longer-term changes are not yet detectable in the limited-duration observational irradiance record. However, estimates of historical solar irradiances are possible by using solar activity proxies to parametrize irradiance variability mechanisms—such as the influences of sunspots, faculae and network as quantified for the present-day irradiance record. Figure 5(a) shows a reconstruction of the 11-year total irradiance cycle, alone, since 1610, whereas in figure 5(b) the 11 year irradiance cycle is combined with an assumed longer-term irradiance variability component. Adopting this longer-term component permits better agreement between the irradiance reconstruction and both the geomagnetic and cosmogenic isotope records, the latter of which are also shown in figure 5(b).

Total irradiance increased by about 0.25% from 1650 to the present, according to the historical reconstruction shown in figure 5. A variety of similar techniques yield estimates of long term total irradiance variability in the range of 0.2 to 0.5%. At UV wavelengths, long term spectral irradiance changes are estimated to be factors of two larger than the solar cycle changes. But these estimates of the Sun's irradiance variability on historical time scales



are by necessity highly speculative; and they will remain so until the observational record is of sufficient length to establish that long-term irradiance variability is in fact present, in addition to the confirmed variability during the 11 year cycle and on shorter time scales.

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